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Letter

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Evidence for a $K^\pi = 1/2^+$ isomer in neutron-rich ^{185}Ta

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Abstract. Excited states in neutron-rich ^{185}Ta have been populated following the one-proton pickup reaction of ^{186}W(^{18}O,^{19}F). In-beam γ-rays were measured in coincidence with scattered particles detected by a high-resolution ΔE-E Si telescope for reaction channel selection. Several low-lying levels including a $T_{1/2} = 0.9(3)$ μs isomer at 406 keV have been identified. A spin assignment of $I = 3/2$ and the $1/2^+[411]$ Nilsson configuration are given to the isomer in comparison with the level energy systematics and the isomer decay rates in the region.

PACS. 21.10.Tg Lifetimes – 23.20.Lv γ transitions and level energies – 25.70.Hi Transfer reactions – 27.70.+q $150 \leq A \leq 189$

In neutron-deficient $A \approx 180$ nuclei, low-lying one-quasiparticle isomers due to the K quantum number conservation (where K is defined as the angular-momentum projection on the nuclear symmetry axis) are systematically observed. This type of isomer is also expected in nuclei at the neutron-rich side of the valley of β stability. The technique using deep inelastic reactions [1–3] and relativistic fragmentation [4] has been developed to access to such nuclei. Recently, ^{18}O-induced transfer reactions were employed to investigate near-yrast structure of neutron-rich nuclei in the $A \approx 180$ [5] and 240 [6–8] regions. In these studies, the two-neutron stripping reaction of (^{18}O,^{16}O) and the two-proton pickup reaction of (^{18}O,^{20}Ne) were used. In addition to these reaction channels, neutron-rich isotopes can be produced via the one-proton pickup reaction of (^{18}O,^{19}F). Here we report the identification of several low-lying levels including a new isomer in neutron-rich ^{185}Ta produced following the ^{186}W(^{18}O,^{19}F) one-proton pickup reaction.

The present experiment was performed at the tandem accelerator facility [9] at Japan Atomic Energy Agency. Excited states of ^{185}Ta were populated using the one-proton pickup reaction ^{186}W(^{18}O,^{19}F). A 180 MeV ^{18}O beam was incident on a self-supporting target of ^{186}W enriched to 98.2%. The target was made of two stacked 450 μg/cm^2 metallic foils and thick enough to stop target-like nuclei inside the target material. Outgoing ions were detected by four sets of surface barrier Si ΔE-E detectors with a diameter of 20 mm. These detectors were placed at 28° with respect to the beam direction. Emitted γ-rays were measured with seven HP-Ge detectors, in coincidence with outgoing ions. Four of these detectors were arranged symmetrically in a plane perpendicular to the beam axis, and the γ-ray anisotropy with respect to the reaction plane was obtained for the determination of transition multipole orders [6]. The time difference (Δt) between signals from the Si and Ge detectors was measured by time-to-amplitude converters (TAC). The energy and time information on outgoing ions and γ-rays was recorded event by event on magnetic tapes. A total of 1.6×10^8 and 6.8×10^7 events for particle-γ and particle-γ-γ coincidences, respectively, were collected. The details of the experimental setup are described in ref. [5].

An E-ΔE plot for outgoing ions measured by the Si detectors is shown in fig. 1. Each ions are clearly separated according to the mass and atomic numbers. The particle

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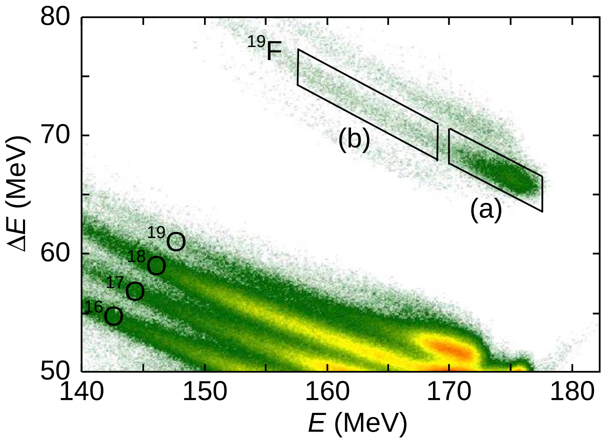

Fig. 1. An E-ΔE plot for outgoing ions measured by the Si detectors. The enclosed areas represent the gate windows with kinematic energies of 170–178 MeV (a) and 157–169 (b), see fig. 2.

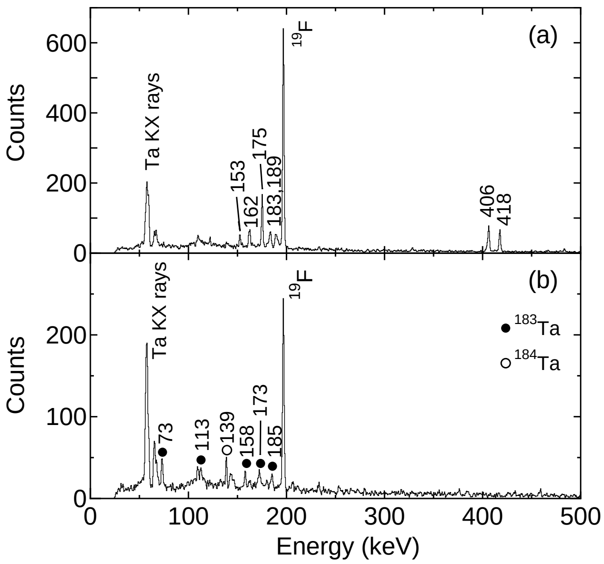

Fig. 2. γ-ray energy spectra gated on ^{19}F ions with kinetic energies of 170–178 MeV (a) and 157–169 MeV (b), corresponding to the gate windows (a) and (b) shown in fig. 1. The γ-rays assigned to ^{185}Ta (a) and ^{183,184}Ta (b) are labeled in units of keV. An intense peak at 197 keV is the transition from the $5/2^+$ state to the ground state in ^{19}F.

energies were calibrated assuming that the most intense peak in the E-ΔE plot corresponds to elastically scattered events of ^{18}O ions entering at the center of the each Si detector. Figure 2 shows a γ-ray energy spectrum gated on ^{19}F ions with different kinetic energies shown in fig. 1. In figs. 2 (a) and (b), γ-ray peaks from ^{185}Ta and ^{183,184}Ta, respectively, are observed. The ^{183,184}Ta nuclei can be produced by two- and one-neutron evaporation from ^{185}Ta when the compound-like ^{185}Ta is excited above the neutron separation energies. Note that an intense 197 keV peak observed in fig. 2 corresponds to the transition from the $5/2^+$ state to the ground state in ^{19}F.

Figure 3 shows a level scheme for ^{185}Ta deduced from the present experimental data. Excited levels in this nucleus have been studied via (t,α) transfer reactions [10] and deep inelastic reactions [11]. Several levels previously identified in the (t,α) transfer reactions are confirmed with the slightly different excitation energies of $\Delta E \lessapprox 10$ keV. This discrepancy is likely due to the low-energy resolution of the earlier measurement. The ground states in ^{185}Ta and the lighter odd-A Ta isotopes with $N \geq 102$ are assigned the $7/2^+[404]$ Nilsson configuration [12]. A 153 keV level which would correspond to a 163 keV state observed in the (t,α) transfer reactions [10] is tentatively assigned as a 9/2 member of the ground-state band. A $K^\pi = 9/2^-$ strongly coupled band, based on the $9/2^-[514]$ Nilsson configuration, is known from the previous studies [10,11]. The present data confirm this up to $I^\pi = (15/2^-)$.

A new level at 418 keV is fed by a 467 keV transition from an 885 keV state which is likely a 890 keV, $7/2^-[523]$ state previously observed in the (t,α) transfer reactions [10]. The γ-ray anisotropy data suggest $\Delta I = 1$ assignments for the 418 and 467 keV transitions, leading an $I = 5/2$ assignment for the 418 keV state. In ^{181}Ta and ^{183}Ta, $I = 5/2$ states, assigned the $5/2^+[402]$ Nilsson configuration, are known at 482 and 459 keV, respectively [12]. From this comparison, the $5/2^+[402]$ assignment is preferred for the 418 keV state in ^{185}Ta.

The analysis of delayed coincidence spectra reveals a sub μs isomer, decaying directly to the ground state via a 406 keV transition. The γ-ray anisotropy data are consistent with $\Delta I = 2$ for this transition. This supports an $I = 3/2$ or $11/2$ assignment for the 406 keV isomer. Unresolved $I = 1/2$ and $3/2$ states, based on the $1/2^+[411]$ Nilsson configuration, were previously observed at approximately 409 keV in the transfer reaction experiment [10]. As discussed below, the observed isomer is presumably the $I = 3/2$, $1/2^+[411]$ state. Note that $K = 3/2$ and $11/2$ states originating from the spherical $2d_{5/2}$ and $1h_{11/2}$ orbitals are expected at high excitation energy and therefore the $K = 3/2$ or $11/2$ assignment is unlikely for the 406 keV isomer.

Above the isomer, several transitions are observed in the delayed γ-ray spectrum gated on the 406 keV transition (see fig. 4). Two transitions at 183 and 189 keV feed the 406 keV isomer from near-degenerate levels at 589 and 595 keV. The γ-ray anisotropy data suggest $\Delta I = 1$ and 2 for the 183 and 189 keV transitions, respectively, supporting $I = 5/2$ and $7/2$ assignments for the 589 and 595 keV states. In the previous transfer reactions [10], a 590 keV level was identified as $I = 5/2$ and $7/2$ doublet states in the $1/2^+[411]$ band. Considering the uncertainty of the measured energies, the 589 and 595 keV states likely correspond to this doublet. The present data add two higher-lying 9/2 and 11/2 members at 888 and 901 keV to this band. In addition, three levels are observed at 734, 810 and 889 keV, forming a rotational-like structure. No detailed information for these transitions are obtained.

The half-life of the 406 keV isomer was determined as $T_{1/2} = 0.9(3)$ μs from the analysis of particle-γ time difference data shown in the inset of fig. 4. Electromagnetic

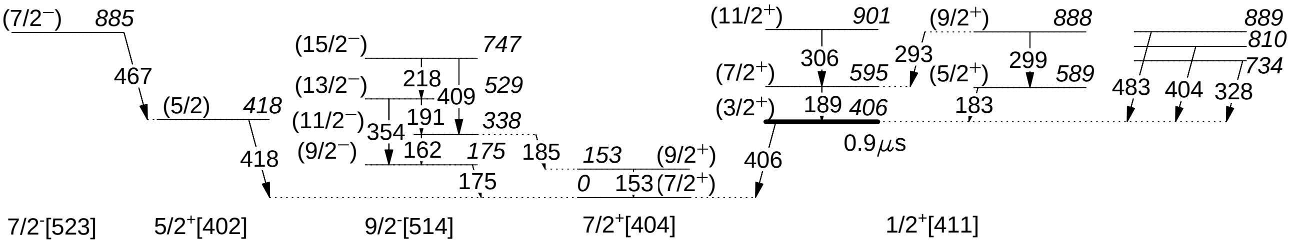

Fig. 3. A proposed level scheme for ^{185}Ta. The Nilsson configurations are shown to the bands. The γ-ray and level energies are given in units of keV.

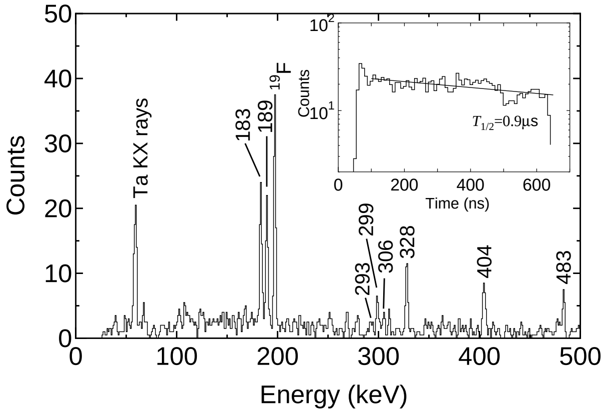

Fig. 4. A delayed coincidence spectrum gated on the 406 keV transition, showing transitions above the isomer at 406 keV. The inset panel shows a particle-γ time difference spectrum for the 406 keV transition.

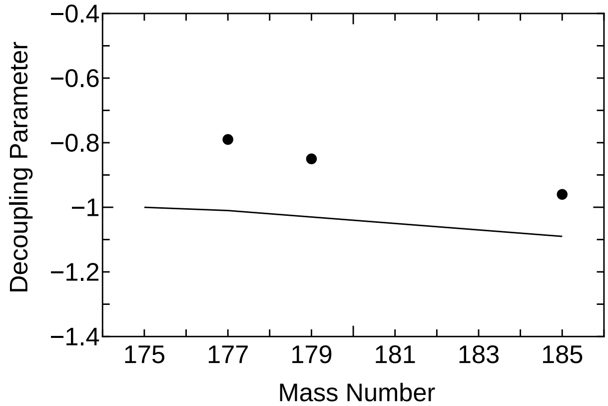

Fig. 5. Decoupling parameters for the $1/2^+[411]$ band in ^{177}Ta, ^{179}Ta [13] and ^{185}Ta are plotted in filled circles. The values predicted by the Nilsson model are shown with a solid line. The deformation parameters used are $(\epsilon_2, \epsilon_4) = (0.250, 0.034)$ for ^{175}Ta, $(0.251, 0.044)$ for ^{177}Ta, $(0.249, 0.054)$ for ^{179}Ta, $(0.245, 0.066)$ for ^{181}Ta, $(0.235, 0.070)$ for ^{183}Ta, and $(0.220, 0.070)$ for ^{185}Ta.

transitions involving the K change greater than the transition multipolarity, *i.e.,* $\Delta K > \lambda$, are forbidden in the K selection rule. This type of transitions can be discussed in terms of the hindrance factor $F = T^{\gamma}_{1/2}/T^{W}_{1/2}$ or the hindrance factor per degree of K forbiddenness $f_\nu = F^{1/\nu}$, where $T^{\gamma}_{1/2}$ is the partial γ-ray half-life, $T^{W}_{1/2}$ is the corresponding Weisskopf single-particle estimate, and ν is the order of K forbiddenness ($\nu = \Delta K - \lambda$). The 406 keV isomer decays to the ground state via the K-forbidden $E2$ transition with $\nu = 1$. Assuming that the 406 keV isomer decays only by the 406 keV, pure $E2$ transition, the value of $f_\nu = 1.1 \times 10^3$ is obtained. This is in accordance with the value of $f_\nu = 2.4 \times 10^3$ obtained for the corresponding $\Delta K = 3$, $E2$ transition in ^{181}Ta (The $I = 3/2$, $1/2^+[411]$ state in ^{181}Ta has the shorter half-life of 0.87 ns because of a dominant fast decay branch to the $I = 5/2$, $5/2^+[402]$ state [12].) This supports the $I = 3/2$, $1/2^+[411]$ assignment for the 406 keV isomer.

The $I = 1/2$, $1/2^+[411]$ bandhead has not been identified. The decay of this state would require γ-ray transitions of $M3$ or higher multipolarity, and from the partial half-life of the corresponding transitions in ^{177,179}Lu and ^{181}Ta [12], the half-life of the unobserved $1/2^+[411]$ bandhead in ^{185}Ta would be expected to be in the millisecond range. Since the measurable half-life of isomers in the present experimental setup is limited to less than ~ 5 μs, on account of the 1 μs TAC range, such long-lived isomers cannot be observed.

The $1/2^+[411]$ bandhead and its rotational levels have been identified in ^{177,179}Ta as well as odd-A Tm and Lu isotopes [12]. As the decoupling parameter for this band typically ranges from -0.61 to -0.99 [13], the $I = 1/2$ and $3/2$ rotational members have a small energy spacing. Similarly, the $I = 5/2$ and $7/2$ band members are almost degenerate as the case of ^{185}Ta. The observed lowest three levels of the $1/2^+[411]$ band in ^{185}Ta give the decoupling parameter of $a = -0.96$. The decrease of the decoupling parameter with increasing the mass number in the Ta isotopes ($a = -0.79$ for ^{177}Ta and $a = -0.85$ for ^{179}Ta [13]) is a characteristics known for the $1/2^+[411]$ band in the Tm and Lu isotopes [13].

In fig. 5, the decoupling parameters in Ta isotopes are compared with values predicted by the Nilsson model. The Nilsson parameters were taken from ref. [14] and the $\Delta N_{\rm osc} \neq 0$ couplings resulting from the hexadecapole deformation were neglected. The quadrupole (ϵ_2) and hexadecapole (ϵ_4) deformation parameters were extracted by the potential energy surface calculation using the standard Nilsson-Strutinsky method. The decreasing trend of the decoupling parameter with increasing the mass number, largely due to the deformation changes (see the caption to fig. 5), is reproduced by the present Nilsson model calculation. The energy spacing between the $I = 3/2$ and unobserved $I = 1/2$ states in ^{185}Ta is also deduced from the observed level energies as $\Delta E = 2.4$ keV. This is consistent with the trend in the lighter Ta isotopes for increasing mass number and the smaller energy spacing ($\Delta E = 9.8$ keV for ^{177}Ta, $\Delta E = 7.3$ keV for ^{179}Ta and $\Delta E = 3.8$ keV for ^{181}Ta [12]).

In summary, a $T_{1/2} = 0.9(3)$ μs isomer at 406 keV has been identified in neutron-rich ^{185}Ta via the one-proton pickup reaction of ^{186}W(^{18}O,^{19}F). From the comparison with the previous transfer reaction data, the $I = 3/2$, $1/2^+[411]$ assignment has been given to this isomer. The decoupling parameter extracted for the $1/2^+[411]$ band lies in the trend known for the odd-A Tm, Lu and Ta isotopes in the region. The small energy spacing of $\Delta E =$ 2.4 keV was also deduced between the $I = 1/2$ and $3/2$ states in the $1/2^+[411]$ band. The unobserved $I = 1/2$, $1/2^+[411]$ bandhead is expected to decay to the $7/2^+[404]$ ground state via $M3$ or higher multipole transitions, with a long half-life in the millisecond range.

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